Project Closeout Report

ARRA Electron Lens

at the
Collider-Accelerator Department
at
Brookhaven National Laboratory
Upton, NY

for the
U.S. Department of Energy
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**Project Closeout Report for Electron Lens
at the
Collider-Accelerator Department
at
Brookhaven National Laboratory**

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1. Introduction

The polarized proton luminosity is limited by the beam-beam interaction, which leads to tune shifts and spreads in the beam. So far total beam-beam induced tune spreads of 0.015 with 2 beam-beam collisions were reached in RHIC, and bunches with 1 collision have better lifetimes than bunches with 2 collisions (see Figure 1).

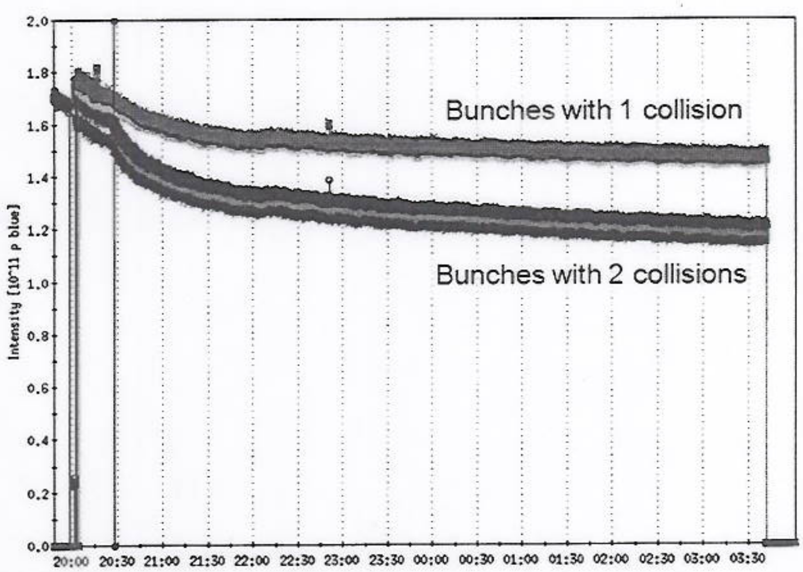

Figure 1: Beam lifetime of bunches with 1 and 2 head-on beam-beam collisions in RHIC (Run-8). Most bunches encounter 2 collisions and the electron lenses will compensate one of the beam-beam collisions.

When the proton beams also collide with a low energy electron beam (electron lens), the beam-beam induced tune spread can be partially compensated. With such compensation, one can either increase the bunch intensity or decrease the beam emittance, leading to higher luminosity.

Complete head-on beam-beam compensation requires 3 conditions:

1. The amplitude dependent force exerted on a proton by the proton and electron beam is the same (i.e. both beams have a Gaussian profile).
2. The phase advance between the proton-proton and electron-proton collision is a multiple of π.
3. There are no nonlinearities between the proton-proton and electron-proton collision.

In practice these conditions can only be met approximately but even under imperfect compensation the tune spread can be reduced and the beam lifetime improved for large enough beam-beam parameters ξ.

Two electron lenses were installed in the Tevatron where they were used as gap cleaner, and have been shown to increase the beam lifetime of selected antiproton bunches suffering from

PACMAN effects. The Tevatron electron lenses were not used as head-on beam-beam compensators (only one of the lenses had a Gaussian profile temporarily for test purposes).

Simulations have shown that the head-on beam-beam effect should only be compensated partially. Our goal is to reduce the beam-beam induced tune spread only to values that can be accommodated in the tune diagram. Since the beam-beam parameter is only linearly dependent on the bunch intensity ($\xi \propto N_b$) but the luminosity quadratically ($L \propto N_b^2$), gains in ξ translate in about twice that amount in L.

The electron lenses were reviewed by the C-AD Machine Advisory Committee in 2009, where it was stated, "the proposal for an operational demonstration is strongly supported". The lenses were further reviewed by C-AD Machine Advisory Committee in 2010, 2011, and 2012, the superconducting solenoids was reviewed in 2010, and BNL ARRA projects were reviewed in 2010 and 2013.

2. Management

The Federal Program Manager for the Electron Lens ARRA AIP project was James Sowinski and the Contractor Project Manager at BNL was Wolfram Fischer.

3. Project Baseline

3.1. Technical Scope and Deliverables Baseline

The project scope was to engineer, design, fabricate and test the components for one electron lens, such that the lens was ready for installation during a RHIC shutdown. Major fabrications included the onsite fabrication of a superconducting magnet and correctors, plus an electron gun and collector. Major procurements included 6 warm solenoids and 4 warm orbit correctors as well as power supplies for the gun, transport and collector.

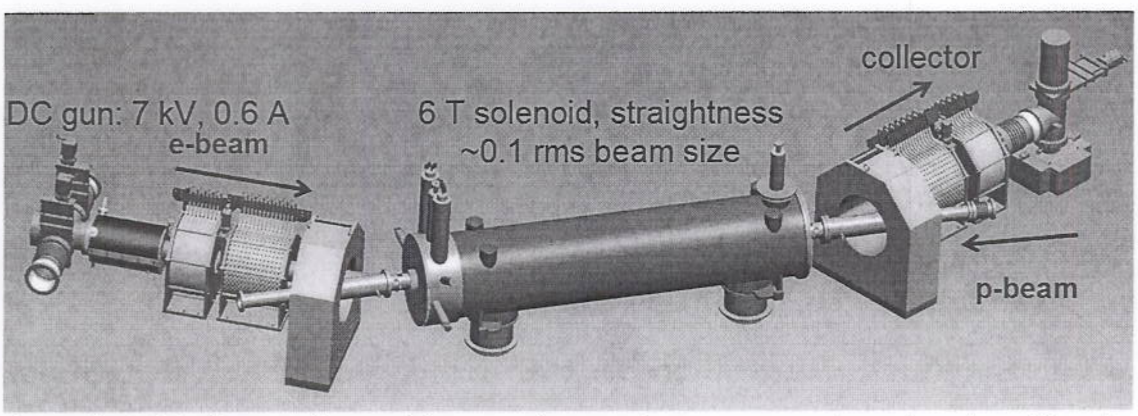

Figure 2: RHIC electron lens with gun, electron beam transport, main solenoid and collector. The electron interacts with the proton beam inside the main solenoid.

In January 2013 all criteria required for successful completion of the project had been accomplished:

All components were ready for installation in the RHIC interaction region and the following 2 critical parameters had been verified:
(1) A minimum field of 5 T in the superconducting solenoid as measured in a vertical test.
(2) 10% of the nominal electron beam current transported from the gun to the collector on a test bench with the superconducting solenoid.

3.2. Cost Baseline

The Total Project Cost was $4M dollars, funded by American Recovery and Reinvestment Act (ARRA) funds. All ARRA funding was received. It was estimated that approximately $1.3M (32%) of the ARRA funds would be spent on labor and the remaining $2.7M (68%) spent on material and equipment. The actual costs show that 37.5% was spent on labor and 62.5% on material.

There was no project contingency.

3.3. Milestone Performance

The chart below shows the project milestones, some of which were reportable for ARRA funding purposes. Milestones related to the manufacture of the superconducting solenoid are shown as (SMD). It was planned that the Gun and Collector would be completed at the same time but did not, so their respective completion dates are detailed in the table.

Electron Lens ARRA AIP Milestones	planned Q/FY	actual mo/yr	ARRA milestones
Obligate Funding to BNL	3QFY09	Jun-09	x
Solenoid, including power supply ready to order	4QFY09	Jul-09	x
Gun & Collector ready to order	1QFY10	Feb-10	x
Beam Transport ready to order	2QFY10	Jun-10	x
Diagnostics ready to order	3QFY10	Jul-10	x
Design Review for Superconducting Solenoid	1QFY11	Oct-10	
Electron Lens added to C-AD Safety Analysis Document	2QFY11	Feb-11	
FY11 Installation tasks defined in schedule	2QFY11	Mar-11	
1st delivery - warm solenoid	3QFY11	May-11	
FY12 Installation tasks defined in schedule	3QFY11	Jun-11	
Control System specified	3QFY11	Jun-11	x
Begin installation of utilities	4QFY11	Sep-11	x
Block Corrector Coils Complete (SMD)	4QFY11	Sep-11	
Gun and collector manufactured complete	4QFY11	Mar-11/Dec-11	
Fringe Field Solenoid Coils Complete (SMD)	4QFY11	Sep-11	
Transport solenoids manufactured complete	1QFY12	Mar-12	
Dipole Trim Coils Complete	1QFY12	Jun-12	
Solenoid Vertical test (SMD)	2QFY12	Jun-12	x
Gun and collector test stand measurements complete	3QFY12	Dec-12	
All components tested and ready for installation	3QFY12	Jan-13	
Project complete	3QFY12	Jan-13	x

3.4. Funding

Funding of \$3.6M was received in May 2009, and the remaining \$0.4M in July 2009.

4. Closeout Status

By December 31, 2012 all commitments had been resolved.

5. Transition to Operations

5.1. Performance Parameters

The Ultimate Performance Parameters (UPPs) for both electron lenses consist of:

(1) A minimum main solenoid field of 5 T with the completed magnet.
(2) A maximum deviation of the main solenoid field lines from a straight line of ±50 μm after correction (measured in the final tunnel location, in both transverse planes, at a main field of 4 T, and over a range of at least ±800 mm)
(3) A stable DC electron beam current of 0.9 A with a turn-to-turn current ripple of ≤0.1%

With the parameters (1)-(4) the electron lenses can compensate one of the two head-on beam-beam interactions for a bunch intensity up to 2.5×10^{11} protons. At 100 GeV proton energy, a bunch intensity of 2.5×10^{11} protons will more than double the peak luminosity compared to the last operating period at that energy (Run-12), when the bunch intensity reached 1.6×10^{11} protons.

A successful increase in the average luminosity (parameter (5)) also requires that bunches of 2.5×10^{11} well-polarized protons can be prepared with upgrades in the polarized source (OPPIS), Booster, and AGS; a successful implementation of a lattice with a specific phase advance between the proton-proton and proton-electron beam-beam interactions; and a ratio of peak to average luminosity close the one without electron lens operation. Parameter (5) is formulated for 100 GeV beam energy only since the current multi-year RHIC run plan only foresees polarized proton operation at 100 GeV beam energy, in the 2015-2016 and 2021-2022 time windows. The electron lenses will also yield a luminosity gain at 255 GeV beam energy but it is unknown if and when another run at that energy will take place in the future.

5.2. Schedule

Over the summer 2013 the straightness of the superconducting solenoid field lines will be measured in the final location of the superconducting magnets, and a correction applied to bring the straightness within the specified tolerance. The vacuum system will then be closed again for the Blue lens, and gun, collector and instrumentation installed in the Yellow lens. Before Run-14 the UPPs (1) and (2) should be demonstrated in both lenses.

For the RHIC Run-14 it is planned to operate with Au+Au at beam energies of 7.3 and 100 GeV/nucleon, and possibly with d+Au or h+Au. With Au beams the beam-beam parameter is approximately a factor 3 smaller than with p beams and beam-beam compensation is not possible. Au beams still allow for studying effects such as the detrimental impact of the electron beam on the hadron beam arising from small electron beams, time-dependent electron beam parameters, and ion accumulation in the electron lens. The drift tube system can be commissioned and the backscattered electron detector tested. After Run-14 the UPPs (3) and (4) should be demonstrated in both lenses.

In the summer 2014 hardware and software modifications can be made that are identified during the Run-14 tests. Run-15 is expected to have a 100 GeV polarized proton run, and full commission including head-on beam-beam compensation is possible. This requires a new lattice, and the preparation of well-polarized proton bunches of 2.5×10^{11} intensity. After Run-15 UPP (5) should be demonstrated.

The commissioning milestones are presented below.

Milestones Blue and Yellow electron lenses	Planned Date [Q-FY]	Planned Date [mm-yy]	Actual Date [mm-yy]	Comment
Test 255 GeV proton lattice with $\Delta\psi = k\pi$ between IP8 and IP10	3Q-FY13	Jun-13	Apr-13	
Commission new proton diagnostics (bunch-by-bunch loss monitor and BTF)	3QFY13	Jun-13	Jun-13	
Complete horizontal sc solenoid #1 test in RHIC tunnel (5 T field)	4QFY13	Sep-13	Jun-13	UPP (1) in Blue, FF and AFF operation
Complete horizontal sc solenoid #2 test in SMD hall (5 T field)	4QFY13	Sep-13	Jun-13	UPP (1) in Yellow, FF and AFF operation
Complete Blue lens electron beam commissioning with EBIS spare in RHIC tunnel	4QFY13	Sep-13	Jul-13	UPPs (3) and (4) in Blue
Complete straightness measurement of sc solenoid #2 in tunnel (Yellow lens)	4QFY13	Sep-13	Jul-13	UPP (2) in Yellow
Complete straightness measurement of sc solenoid #1 in tunnel (Blue lens)	1QFY14	Dec-13	Oct-13	UPP (2) in Blue
Install Yellow lens vacuum system, gun and collector	1QFY14	Dec-13		gun and collector new intstallation
Install Blue lens vacuum system	2QFY14	Mar-14		reinstallation after straightness measurement
Both lenses installed and ready for electron beam operation in Run-14 (Au+Au)	2QFY14	Mar-14		run starts beginning of February
Re-commission Blue lens electron beam (1 A DC, Gaussian profile)	2QFY14	Mar-14		UPPs (3) and (4) in Blue
Commission Yellow lens electron beam (1 A DC, Gaussian profile)	2QFY14	Mar-14		UPPs (3) and (4) in Yellow
All electron lens magnets operating concurrently with RHIC operation	2QFY14	Mar-14		orbit and tune effects
Drift tube systems commissioned	3QFY14	Jun-14		for ion extraction with DC beam
BPM systems commissioned	3QFY14	Jun-14		both proton and electron beam
Ion beam transverse damper test	3QFY14	Jun-14		suppresses possible instabilities
Overlap of electron with ion beams	3QFY14	Jun-14		measure effect on proton beam (tune footprint, lifetime)
Test of overlap detector (backscattered electrons)	3QFY14	Jun-14		same number of electrons with Au, but at higher energy
Hardware and software modifications in response to 2014 test runs	4QFY14	Sep-14		to be specified after Run-14
Hardware and software modifications in response to 2014 test runs	1QFY15	Dec-15		to be specified after Run-14
Both lenses ready for Run-15 (p+Au and p+p)	2QFY15	Mar-15		
Commission 100 GeV proton lattice with $\Delta\psi = k\pi$ between IP8 and IP10	3QFY15	Jun-15		different from 255 GeV lattice, larger β^* at IP10
Overlap of electron with proton beams	3QFY15	Jun-15		maximize beam lifetime with higher bunch intensity
Demonstration of average pp luminosity gain	3QFY15	Jun-15		UPP (5)